CRUSTAL STRUCTURE BELOW HUNGARY

by

B. BALKAY

Geophysical Institute, Eötvös University, Budapest
(Received : Sept. 10th, 1958)

SUMMARY

After a definition of the term "crust of the Earth", the information obtained by deep reflection data for the Hungarian part of the crust is analyzed. By a new method called the method of surplus anomalies further information about crustal thickness is drawn from deep drilling and gravity anomaly data. The Hungarian crust is shown to be thinner than the European average and the crustal thickening of the Alps to cease at the western frontier of the country. The evolution of the present weak crust from the rigid one of the Mesozoic is thought to have taken place in two steps of tension accompanied by intense volcanic effusions and followed by subsidence due to isostatic readjustment.

Introduction

In the light of up-to-date geology and geophysics, that part of the Earth which carries the tension and suffers the deformation due to tectonic forces is the crust. The upper part of the crust, accessible to direct tectonical investigation, and consisting to a great extent of sediments of small strength, carries but a small fraction of tectonic load : it has but the role of a strain gage, registering and indicating tectonic deformation. Consequently, for the tectonic history and evolution of a given area, the strength and structure of the crust below is of utmost importance. This is one of the reasons which have accelerated research on crustal structure in most of the world and this is why it is worth while to investigate into crustal structure below Hungary, whose complex geological structure makes it into one of the more puzzling parts of Europe. As will be seen, the understanding of the properties of the underlying crust will to some extent aid the solution of structural problems.

In proceeding to study the Hungarian part of the crust, we will first of all define what we will exactly understand under this term. We will then analyze the distribution of crustal thickness on the hand of geological and geophysical data available and, finally, we will try to give an account of the process that led to the evolution of the present crustal structure.

Definition of the Crust

1. In general opinion, the lower boundary of the crust is defined by the Mohorovičić discontinuity. We will accept this definition, there being no reason to reject it.

2. The problem of the upper boundary of the crust is not nearly as simple. For the upper boundary we may choose the following surfaces :

1. topography,
2. the basement in the geophysical sense,
3. the basement in the geological sense (after Bubnoff),
4. the surface of the crystalline,
5. the surface of the „primordial crust".

Let us consider these surfaces one by one. Topography, for one, has the advantage of being very well-defined and well-known. However, from the point of view of crustal statics, such a definition of the upper crustal boundary is rather misleading, as the more or less thick sedimentary series of small strength will then also belong to the crust, and consequently the strength of a crustal section of one and the same thickness will be much different, depending on the percentage of unconsolidated sediments in the profile. Thus, for the purposes of crustal tectonics, this definition should be avoided.

The basement in the geophysical sense is a surface across which the main parameter of the prospecting method employed (seismic velocity, electrical resistance, density) takes a considerable jump. Consequently, such a basement definition will depend on the geophysical method used and rocks ranging in age from Palaeozoic to Eocene will come to be regarded as the basement in one and the same profile. The equivocality of this definition is a serious disadvantage.

The geologist's basement complex in the sense of Bubnoff is the bulk of intensely folded or faulted, consolidated but not metamorphosed formations. The lower boundary of this unit is coincident with the upper one of the crystalline and/or metamorphosed complex. Both the upper and lower surfaces of the basement complex could be used as the upper boundary of the crust with equal right. However, in the case of Hungary a great number of borings have reached the former one, whereas the latter one has been touched only where the crystalline immediately underlies unconsolidated sediments. On the other hand, from the point of view of strength, the consolidated sediments do not differ much from the bulk of the crust. All in all, the definition of the upper boundary of the crust by the surface of the basement in the above sense seems to be most advantageous.

There remains to be considered the surface of the "primordial crust". However, although theoretically there must have been such a surface, it is impossible in practice to locate it at present, except perhaps in the areas of the ancient shields.

3. Considering the above said, we will define in the following the crust as the zone of rocks situated between the Mohorovičić surface and the geological basement. Somewhat deviating from general usage, we have drawn the stratigraphic limit of the basement complex at the transition upper to lower Cretaceous. The tectonical reason for this was that the most intense period of Alpine orogeny touching Hungary was the Austrian one, occurring just at this time, whereas the geophysical reason was that in the country the average density and seismic velocity of rocks older than upper Cretaceous are but slightly different, while those of the younger rocks are much different from the corresponding parameters of the crust. Where the lower Cretaceous formation is lacking, the surface of the youngest underlying formation beneath is con-

sidered to be the boundary of the crust. Thus, in some areas this surface might be even the surface of the crystalline.

4. As to the subdivision of the crust thus defined, the general subdivision into a granitic and basaltic layer will be accepted. However, the notations „granitic" and „basaltic" will not be considered to refer to petrographic composition, as *a)* the upper layer contains — according to our definition — consolidated sediments as well, and is, according to recent investigations, rather granodioritic in nature, and *b)* the lower layer, if of a basaltoid composition at all, has to be gabbroic rather than basaltic. The notations are considered to refer to the physical parameters of the layers, namely a velocity of longitudinal waves of about 5,6 km/sec for the upper and 6,5 km/sec for the lower layer and a density of 2,67 cgs for the upper and one of 3,0 cgs for the lower layer.

As to the Förtsch discontinuity, observed in Germany by Förtsch (1) and later also by others, it has not yet been demonstrated in Hungary up to now.

The ideal section of the crustal structure as above defined is seen in Fig. 2.

Distribution of crustal thickness

1. Valuable data on crustal structure were yielded by the deep reflexion experiments of Gálfi and Stegena (2, 3). The depth of the Conrad-surface was determined at five points, four of which have also yielded the depth of the Mohorovičić discontinuity. The main results of these experiments are listed in Table I. In comparison with the similarly listed European data it is seen that the seismic velocities are not much different from those of other parts of our continent but that the *thickness of the crust is by some 5 to 7 kilometres less than the European average.*

Table I

Locality	Depth of Conrad discontinuity kms	Depth of Mohorovičić discontinuity kms	v_2 km/sec	v_3 km/sec	Reference
Dunaharaszti Earthquake Jan. 12., 1956	20,20	33,00	5,49	6,98	Bisztricsány-Csomor (4)
Csapod	16,6	19,6	5,8	6,0	Gálfi-Stegena (2)
Hajduszoboszló	19,5	23,0	5,8	6,0	Gálfi-Stegena (2)
Karád	21,1	—	5,8	6,0	Gálfi-Stegena (2)
Hegyhátmaróc	19,5	24,5	5,8	6,0	Gálfi-Stegena (2)
Szalatnak	21,8	28,1	5,8	6,0	Gálfi-Stegena (2)
Haslach	20—22	29—33	5,9	6,5	Förtsch (1)
Helgoland	10,7	27,4	5,6	6,4	Bartels (5)
Caucasus	20	48 ?	5,6	?	Twaltwadse (6)
South Germany	19 ?	31 ?	?	?	Reich (7)
Blaubeuren	20	28	5,9	6,5	Reich (8)
Murnau	17—18	30—31	5,5	6,0	Dohr (9)

In certain regions, as e. g. in the Californian Coast Ranges, most of the information on crustal structure is derived from natural earthquakes. However, Hungary being a greatly aseismic territory, the first seismological crustal analysis was carried out in 1956 by B i s z t r i c s á n y and C s o m o r (4). The results are also seen in Table I. The depth of the Mohorovičić discontinuity is seen to be around the European average ; this was to be expected, as, the depths of the interfaces being averages along the wave paths as shown in Fig. 1., the smaller depth in the Carpathian Basin is compensated by the greater depth across the surrounding mountain chains.

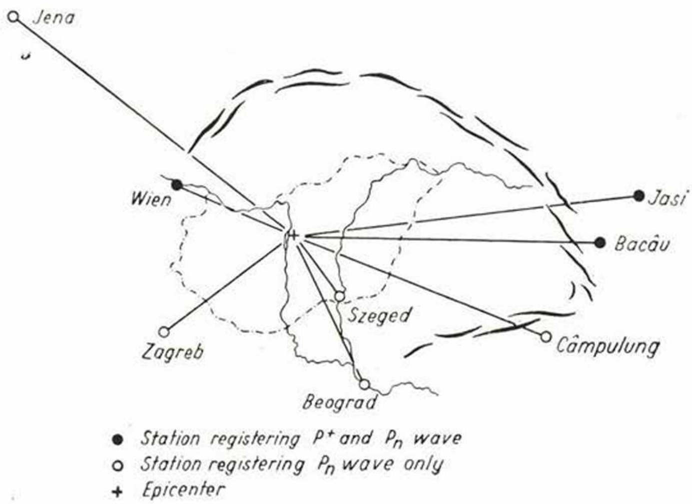

Fig. 1. Wave paths of the Earthquake of January 12, 1956 as analyzed by B i s z t r i c s á n y and C s o m o r (4.)

2. The great disadvantage of deep reflection and refraction work is the high cost, so that the points at which the crustal parameters are determined are, and will continue to be scarce. Although for a time Hungary occupied the first place in Europe as to the areal density of deep reflections, and although further work is planned, the smaller details of crustal relief will not emerge from the results of deep-seismic work only. Therefore a somewhat different approach was attempted, yielding information as to crustal structure on the basis of deep-drilling and gravity material already at hand.

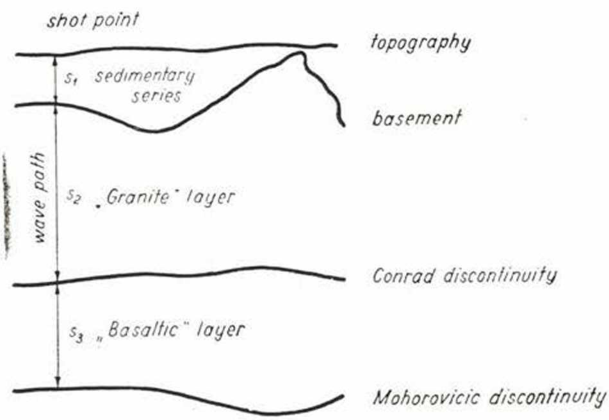

Fig. 2. Ideal section of the crust as defined by the author showing the wave path of a deep reflection wave

The idea utilized thereby was the following: If the unconsolidated sediments are removed from above the basement and substituted by rock of density equalling that of the crust, part of the Bouguer gravity anomaly will be compensated. The remaining part will be due — as the undulations of topography are eliminated by terrain and topographic corrections — to the undulations of the Mohorovičić surface. Disregarding the effect of eventual horizontal density changes in the crust, the remaining gravity anomaly will be roughly inversely proportional to the depth of the Mohorovičić discontinuity. Let us call this remaining part of the Bouguer anomaly the „*surplus anomaly*".

3. To put this principle into practice, it would be necessary to know the average density and thickness of the unconsolidated sediments for a sufficiently close-spaced network of points. For part of the network of deep dril-

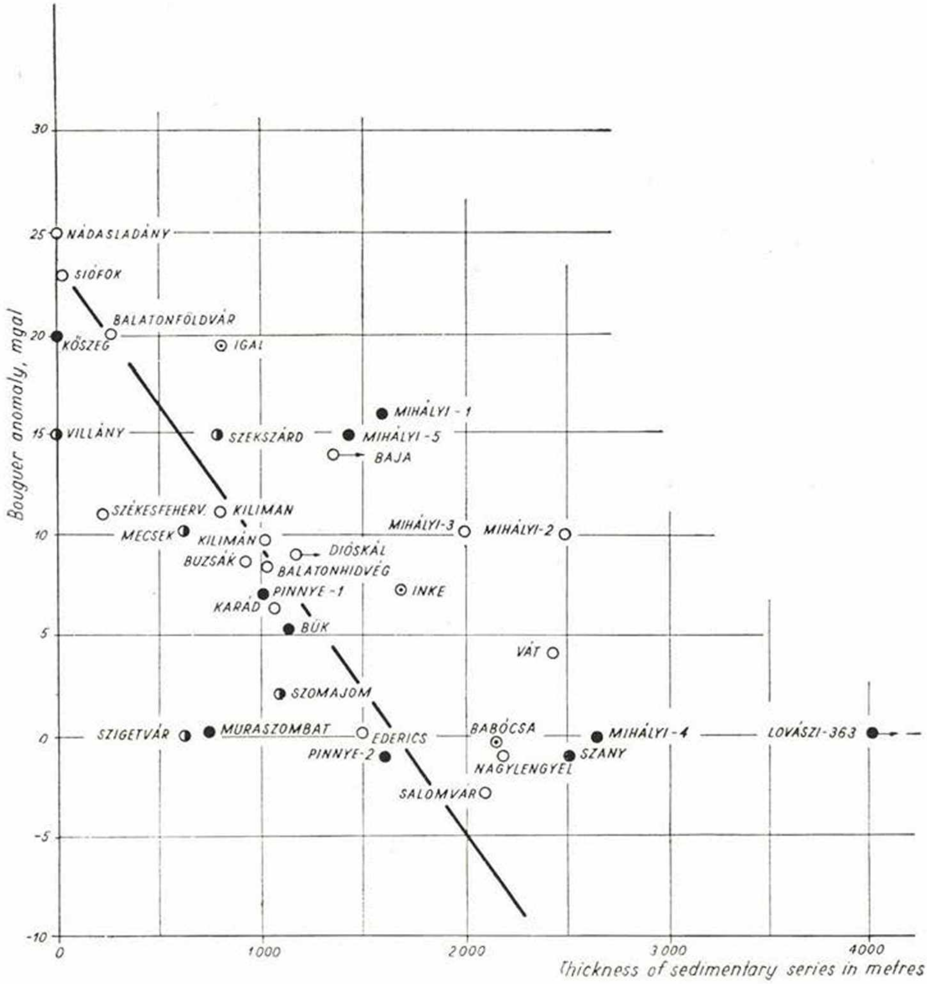

Fig. 3. Basement depth vs. Bouguer anomaly for deep drillings having reached basement; Transdanubia. The dots Mihályi 2—3 and Vát ought to be black ones.

lings in Hungary the thickness of the unconsolidated sediments is known. However, up to now no data concerning the average density of the sedimentary series were published. To circumvent this difficulty, the following method was applied.

We have plotted the Bouguer anomaly for each drilling which reached basement against the depth of the basement, as seen in Figs. 3—4. Fig. 3 contains the drillings of Transdanubia, Fig. 4 those of the rest of the country. If the Mohorovičić interface is supposed to be an equipotential surface and

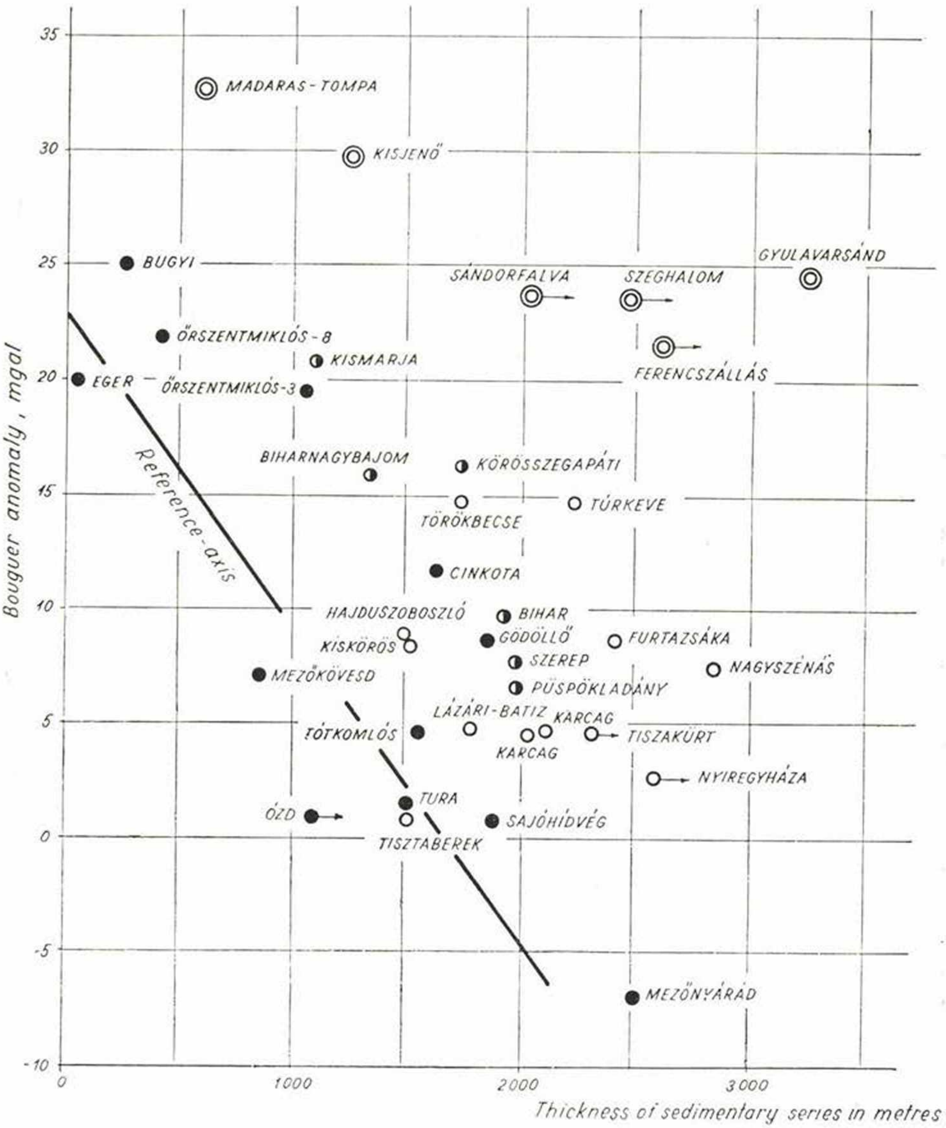

Fig. 4. Basement depth vs. Bouguer anomaly for deep drillings having reached basement: area East of the Danube the average density of the sediments above basement to be constant, the points referring to the individual drillings should be situated along a straight line. The equation of this line can be obtained by substituting in thought the sediments above the basement by a plane parallel horizontal plate whose thickness equals the basement depth and whose density equals the difference of the density of the crust and the average density of the sediments. This is the principle employed also in the well-known Bouguer correction. The equation thus obtained is

$$\Delta g_B = -41{,}9\,(2{,}67 - \sigma_A)\,h + \mathrm{D} \tag{1}$$

where Δg_B is the Bouguer anomaly in milligals, σ_A the average density of the sedimentary series in g cm^{-3}, and h the basement depth in kilometres. The constant term D depends on the system of gravity measurements in which the Bouguer anomaly is considered.

As seen, the points of Diagrams 3—4 fail to fall along this line. The scatter of the points is quite important. However, in the knowledge of the areal distribution of the drillings an interesting relationship is observed: the plots belonging to one and the same structural unit are arranged along parallel straight lines, thus for instance those of the Mihályi structure (black dots in Fig. 3), of the Central Hungarian Mountains (empty dots in Fig. 3), or those north of the Great Plain (black dots in Fig. 4).

The scatter may be due to the fact that we have made two improbable assumptions, namely *a)* that the Mohorovičić interface is an equipotential and *b)* that the average density of the sedimentary profile is constant. It will be shown below that the horizontal variations of the average density of the sedimentary complex cannot result in a point distribution as seen in Fig. 3—4, and that consequently the deviations of the points from a straight line are due to the relief of the Mohorovičić discontinuity.

4. The analysis of some thousands of bulk density data, determined by the Hungarian Oil Trust on drill core samples, has led to the following results: *a)* The average density, as seen in Table II, of the pre-upper Cretaceous rocks as computed from 23 values is exactly 2,67 cgs., confirming what has been said about the definition of the crust. *b)* The average density σ_A of the sedimentary series is 2,23 cgs. Considering this value, the slope of the straight line in (1) is 18,4. The slope of the straight line approximating points of identical structural position in Fig. 3 is 14,9. The agreement is quite good. *c)* The variations of average density are mostly due to the fact that the density of a

Table II

Rock type	Bulk density
Chlorite quartzite	2,72
Chlorite quartzite	2,65
Mica schist	2,60
Mica schist	2,74
Mica schist	2,66
Mica schist	2,58
Mica schist	2,77
Mica schist	2,52
Mica schist	2,68
Mica schist	2,70
„Epimetamorphic rock" ...	2,63
Triassic average (12 data) ..	2,66
Average:	2,67

given kind of sediment — e. g. clay shale — of course varies with depth below surface. The average composition of the sedimentary sequence is quite constant, with clay shale predominating. Exceptions occur only where there are thicker interbeddings of volcanic ash, whose density, however, varies much like that of clay shale. Thus the average density of the sequence will be somewhat smaller where basement depth is small and vice versa. If this variable density is, with the assumption of e. g. a linear variance with depth, introduced into (1), one obtains a parable whose curvature within the considered interval is rather small so that it can be approximated by a straight line. The slope of this line is about 16,0. What is important, however, is that *the variation of average density does not at all explain the structure-dependent scatter of the points,* so that the latter must be due to undulations of the Mohorovičić interface.

5. Let us choose a "normal", reference crust. Let this crust be that underlying the Central Hungarian Mountains. The points along this structural unit are connected by the "reference line" in Figs. 3—4. Now the gravity effect of the Mohorovičić interface's undulation will be given by the ordinate difference in Fig. 3—4 between any point and the point of the "reference line" situated vertically above or below. This ordinate difference is called "surplus anomaly". As a first approximation, let us suppose a linear relation between the depth of the Mohorovičić interface and the amount of sur-

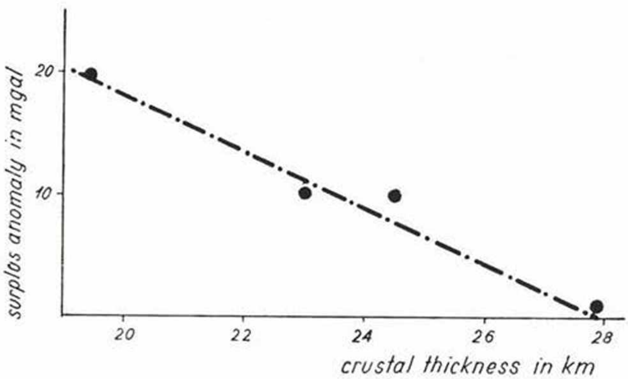

Fig. 5. Crustal thickness vs. surplus anomaly for the deep reflection shot points as given in (2.)

plus anomaly. The constants defining this linear relation may be determined by plotting the depth of the Mohorovičić discontinuity as given at the four Hungarian points of Table I against the surplus anomaly at these points. The result is Fig. 5. The linear relation is seen to prevail. To make the surplus anomalies easier readable, we have constructed a separate axis calibrated in surplus anomaly, as seen in Fig. 6.

6. On the hand of surplus anomaly values, a crustal thickness chart of a given territory may be constructed. For the Western part of Hungary such a chart is shown in Fig. 7. The points having served as a basis for this chart are those represented in Fig. 6. The most important feature shown by this chart is that the *crustal thickening of the Alps* ceases at the western boundary of Hungary and *does not continue below this country.*

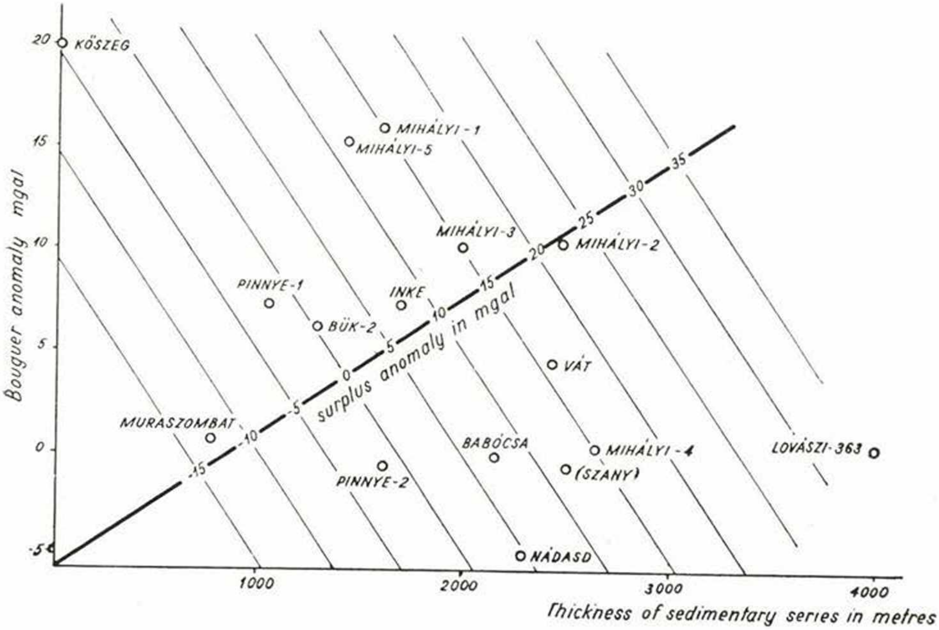

Fig. 6. Surplus anomaly reading graph

7. As to the rest of the country the construction of a crustal thickness chart is under way. Meanwhile let us state that the thickest part of the crust below Hungary occurs in the area of the Mecsek Mountains, while the thinnest points are around Lovászi (Southern part of Fig. 7.) and along the southern border between Danube and Tisza Rivers.

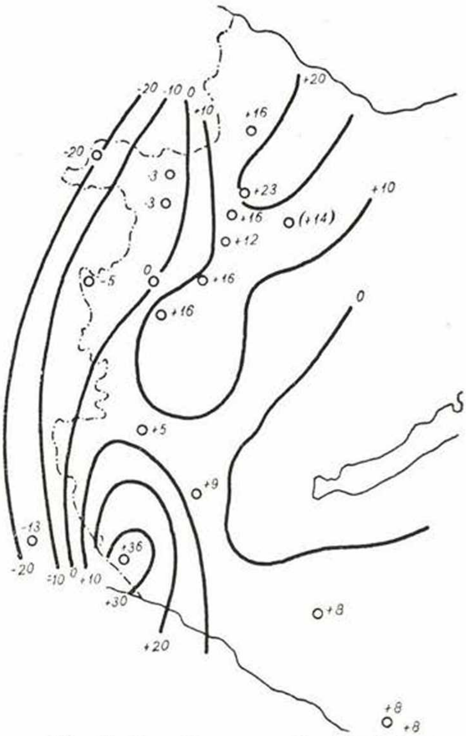

Fig. 7. Surplus anomaly chart for Western part of the country

The geological evolution of present crustal structure

1. The most striking feature of Hungarian tectonics is that while up to the Cretaceous the Carpathian Basin was a most rigid part of the crust, which yielded even to the most intense paroxysms of Alpine mountain building by small-scale folding and overthrusting (Saxonotype tectonics) only, after the Cretaceous its mobility has suddenly increased, became of the same order of magnitude as that of the Alps, and in the Pannonian stage of the Pliocene

even surpassed it. The greatest thickness of post-Sarmatian sediments in the country is over 4000 metres.

The mobility of a given area is more or less accurately reflected by the thickness of the sedimentary series therein formed, excepting when the area is rising. To illustrate the mobility of the Carpathian Basin, as related to that of the Alps, the thicknesses of the sedimentary series of the two areas were compared in Fig. 8. The Alpian data were taken from Kraus (10), the Hungarian ones from the data of deep drillings, mostly those of the Hungarian Oil Trust. It is seen that in the Eocene and Miocene there are two important breaks in the series: in the Eocene the mobility of Hungary is for the first time equal to that of the Alps, while in the Helvetian it surpasses the Alps for the first time.

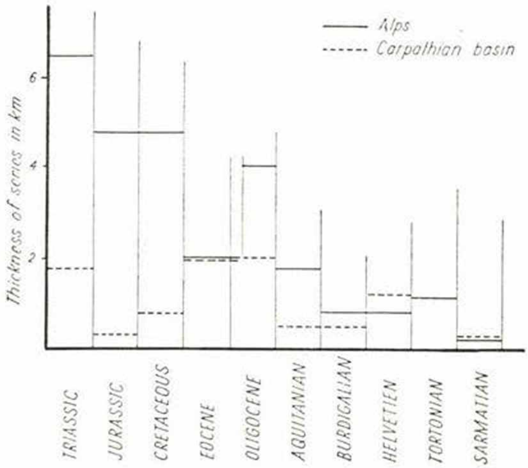

Fig. 8. Mobility of the Hungarian Basin as related to that of the Alps

2. It is very important to note that after a Mesozoic evolution almost entirely lacking volcanism, in the Eocene, and especially in the Miocene, extensive volcanism, mostly andesitic, has taken place in the Carpathian Basin. This is thought to have shattered the formerly so rigid crust. Both phases of volcanism were succeeded by phases of subsidence, of which the first one, in the Oligocene, occurred mostly north of a line of east-northeasterly direction, drawn across Balaton Lake. The greatest amount of subsidence may have been about 1500 metres. The second phase of subsidence has touched most of the country and, as has been stated, its greatest amount was about 4500 metres.

3. As to the tectonics of this volcanism, all evidence seems to indicate that the Hungarian part of the crust was after the Cretaceous subjected to intensive tensile stresses. These have brought about a weakening of the crust and the formation of magma herds by a mechanism e. g. as proposed by Contini (11). After the molten magma thus formed was delivered to the surface, there has begun an isostatic adjustment of the disturbed crust, causing the first phase of subsidence. The process was then repeated at a much larger scale, on the one hand as regards the volcanism: the products of this volcanic period cover about one quarter of the country with effusive series reaching the thickness of 1000 m; and on the other hand, as regards the amount of subsidence.

4. If the idea of the process described in the above point is right, then the area of Hungary has to be at present — the subsidence having come to end — in a state of isostatic equilibrium. That this is indeed so, is indicated by three facts.

a) If on the hand of the deep reflection data we compute the pressures of the four crustal profiles of Table I upon a level of compensation of 40 kms, we obtain the pressure values seen in Table III. The ± 1 per cent deviation may be readily explained by inaccuracies of the data used.

Table III

Locality	Pressure atm.
Csapod	11,932
Hajduszoboszló	11,887
Hegyhátmaróc	11,805
Szalatnak	11,735

b) The map of thickness of post-Sarmatian sediments as compiled by Kertai (12) shows an antiparallelism to the distribution of crustal thicknesses as determined from surplus anomaly data. With other words : where the crust is thinnest, there the post-Sarmatian sediments are thickest, and *vice versa*. This is in exact agreement with the principle of isostasy.

c) On considering the isostatic and Bouguer anomaly map of Hungary as proposed by Facsinay and Szilárd (13) one sees that the two are almost exactly identical. This indicates that the "isostatic" anomalies are mostly due to above-crustal uncorrected density differences and that the true isostatic anomaly in most of the country should be very small.

Acknowledgements

The author wishes to thank the directory and the colleagues of the *Hungarian Oil Trust* to have made available the deep-drilling and bulk density data used in preparing this paper.

REFERENCES CITED

1. Förtsch, O.: Analyse der seismischen Registrierungen der Grosssprengungen bei Haslach im Schwarzwald am 8. April, 1948, *Geol. Jahrb.* **66**, 1952.

2. Gálfi, J. and Stegena, L.: Szeizmikus reflexiós méréssel meghatározott néhány adat a földkéreg magyarországi részéről (Some data on the crustal structure below Hungary as determined by the reflection seismic method). *Geofizikai Közlemények*, **6**, 1957.

3. Gálfi, J. and Stegena, L.: Tiefenreflexionsversuche in Ungarn zum Studium der kontinentalen Aufbaung, *Geologische Rundschau*, **46**, 1947.

4. Bisztricsány, E. and Csomor, D.: Microseismical evaluation of the earthquake of January 12, 1956, and the crustal structure of the Hungarian basin. *Acta Geol. Ac. Sci. Hungaricae*, **5**, 1958.

5. Bartels, J.: Wissenschaftliche Ergebnisse der geophysikalischen Beobachtungen der Sprengung auf Helgoland, *Geol. Jahrbuch*, **64**, 1950.

6. Twaltwadse, G.: Stroenie zemnoi kory v verchnei Kartli, *Soobscheniya Ak. Nauk Grusinskoi SSR*, **9**, 1950.

7. Reich, H.: In Süddeutschland seismisch ermittelte tiefe Grenzflächen, *Geologische Rundschau*, **46**, 1957.

8. Reich, H.: Über seismische Beobachtungen der PRAKLA...., *Ztschr. d. d. geol. Ges.*, **104**, 1952.

9. Dohr, G.: Ein Beitrag der Reflexionsseismik zur Erforschung des tieferen Untergrundes, *Geologische Rundschau*, **46**, 1957.

10. Kraus, E.: Baugeschichte der Alpen, *Akademieverlag*, Berlin, 1951.

11. Contini, C.: Terremoti, vulcani e giacimenti di vapore naturale, *Annali di Geofisica*, **9**, 1956.

12. Kertai, Gy.: A magyarországi medencék és a kőolajtelepek szerkezete a kőolajkutatás eredményei alapján (Structure of the Hungarian basins and oil fields as determined by results of oil prospecting), *Földtani Közlöny*, **87**, 1957.

13. Facsinay, L. and Szilárd, J.: A magyar országos gravitációs alaphálózat (The base network of gravity stations in Hungary), *Geofizikai Közlemények*, **4**, 1956.